

## DAVIDSON LABORATORY

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July 1971

### SOIL STUDIES - AN INVESTIGATION INTO THE PROPERTIES OF THE SOIL-WHEEL INTERFACE

Part 2 - Results of Tests With a Rotating Cone in Sand

by

Louis I. Leviticus

prepared for

U. S. Army Tank-Automotive Command

under

Contract DAAE-07-69-C-0356

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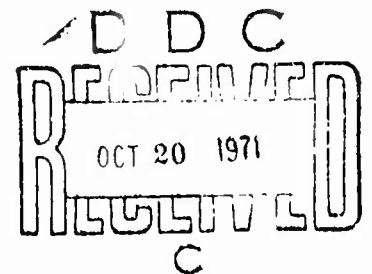
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I. Robert Ehrlich, Manager  
Transportation Research Group

ABSTRACT

Using a rotating cone, a study was made to determine the velocity dependent shear property of various soils. In the wide variety of soils tested including clays, wet and dry sands, no discernible velocity dependent shear properties were measured.

Keywords

Soil Mechanics

Trafficability

Mobility

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## LIST OF SYMBOLS

$H$	Depth of penetration of cone tip	in
$T$	Torque	oz. in, lb in
$W$	Vertical load on cone	lb
$T_c$	Torque, from moving average curve	oz. in, lb in
$H_c$	Depth of penetration of cone tip, from moving average curve	in
$R_T$	Torque ratio	
$R_H$	Depth ratio	
$G$	Cone index gradient	psi/in
$CI$	Cone Index	psi
$V$	Cone velocity	rpm
$\dots_0$	Subscript denoting base or standard velocity	
$C_1$	Constant from the normal vs shear stress curve	psi
$C_2$	Constant from the normal vs shear stress curve	
$\Omega_c, \Omega_s$	WES mobility numbers for clay and sand respectively	
$\alpha$	Coadhesive coefficient	psi
$\mu$	Frictional coefficient	
$\tau$	Shear stress at interface	psi
$\sigma$	Normal stress at interface	psi

SOIL STUDIES - AN INVESTIGATION INTO THE PROPERTIES OF THE SOIL-WHEEL INTERFACE

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INTRODUCTION

The purpose of this investigation was to verify the existence of velocity dependent soil-wheel interface parameters as postulated and developed in the first part of this study.<sup>1</sup> The basic premises for the theoretical considerations were:

- a. There exist soil-rigid bodies interface properties which manifest themselves when relative moment occurs.
- b. The interface properties are velocity dependent.
- c. The interface properties can be separated into cohesive and frictional properties.

In order to determine these properties, a mechanism is needed which can generate relative movement of the rigid body with respect to the soil mass at various velocities.

Moreover, it is required that the phenomenon as it occurs, will have sufficient similarity to the phenomena occurring near a moving soil-wheel interface to warrant the use of those parameters.

Due to financial restraints, the testing was performed mainly on sand. The tests performed on clay were not numerous enough to result in reliable conclusive data and are therefore not included in this report.

During the execution of this work a study was published on soil wheel interaction at high speeds<sup>2</sup>. The author conducted tests of full size aircraft landing gear wheels at velocities up to about 100 knots. The soils used were a buckshot clay and a river sand. The tests showed a reduction of drag load and rut depth with increasing velocity up to about 20 knots. After this minimum the drag load and rut depth increased to a maximum in the vicinity of 40 knots. It was tentatively assumed that up to 20 knots no inertial effects took place. Below this threshold one would expect that the viscous effects dominate. The tests conducted with the cone were at lower velocities, up to about 10 knots. Also our tests were so far conducted only on a sand. Thus our data are not directly comparable with the data in the paper.

The author used a modified version of the WES sand and clay mobility numbers. The modification does result in two dimensional mobility numbers.

$$\Omega_c = \frac{CI(bd)}{F_t} \frac{\delta_t^{1.2}}{h_t^{.5}} \quad [L^{.7}]$$

$$\Omega_s = \frac{G(bd)^{3/2}}{F_t} \frac{\delta_t^{1.5}}{h_t} \quad [L^{.5}]$$

where

- CI = Cone Index (psi)
- G = Cone index gradient (psi/in)
- $\ell$  = Wheel width (in)
- d = Wheel diameter (in)
- $F_t$  = Drag force (lb)
- $h_t$  = Tire section height (in)
- $\delta_t$  = Tire deflection (in)

These dimensions may be part of the reason for some of the differences between the theoretical and empirical curves since  $\Omega_c$  and  $\Omega_s$  are both used in the rut depth prediction equation and in the drag force equation.

The nature of the empirical drag force curves in the first region for a sandy soil do show a similar trend as did the torque versus velocity data for the rotating cone.

Additional work was performed at WES by Turnage<sup>3</sup> who penetrated cones at different velocities in the soil. It is not clear at this point how the results of our rotation tests can be compared to the penetration tests.

Design of the Instrument

The design consisted of a cone mounted on a shaft and driven by a servo-controlled motor (Figs. 1,2,3).

Drive motor, bearings, cone and velocity transducer are mounted on a plate, which is attached to a second plate by means of a set of radial arms which allow small radial movement. This movement is sensed by a Shaevitz LVDT and calibrated with a known torque input (Figure 2).

The force of penetration is measured by a Lebow load cell mounted below the sample tray. A position crank is used to zero the sinkage measuring potentiometer and the sample is pulled upward along the shafts against the cone by the weights in the two weight pans. This type of operation was developed because:

- a. The cone finds its own depth under the actual applied weight.
- b. The accuracy of measurement is improved since the weight of the soil sample is much less than that of the cone, drive motor and torque transducing system.
- c. The load on the sample can be recorded continuously while the test is run.
- d. The removal of the sample and insertion of a new sample is made easier.
- e. The drive system and transducers could be mounted more rigidly on the framework of the machine.

Two stainless steel cones were made having apex angles of  $30^{\circ}$  and  $60^{\circ}$ . The  $30^{\circ}$  cone was 5" high and the  $60^{\circ}$  cone was 4" high.

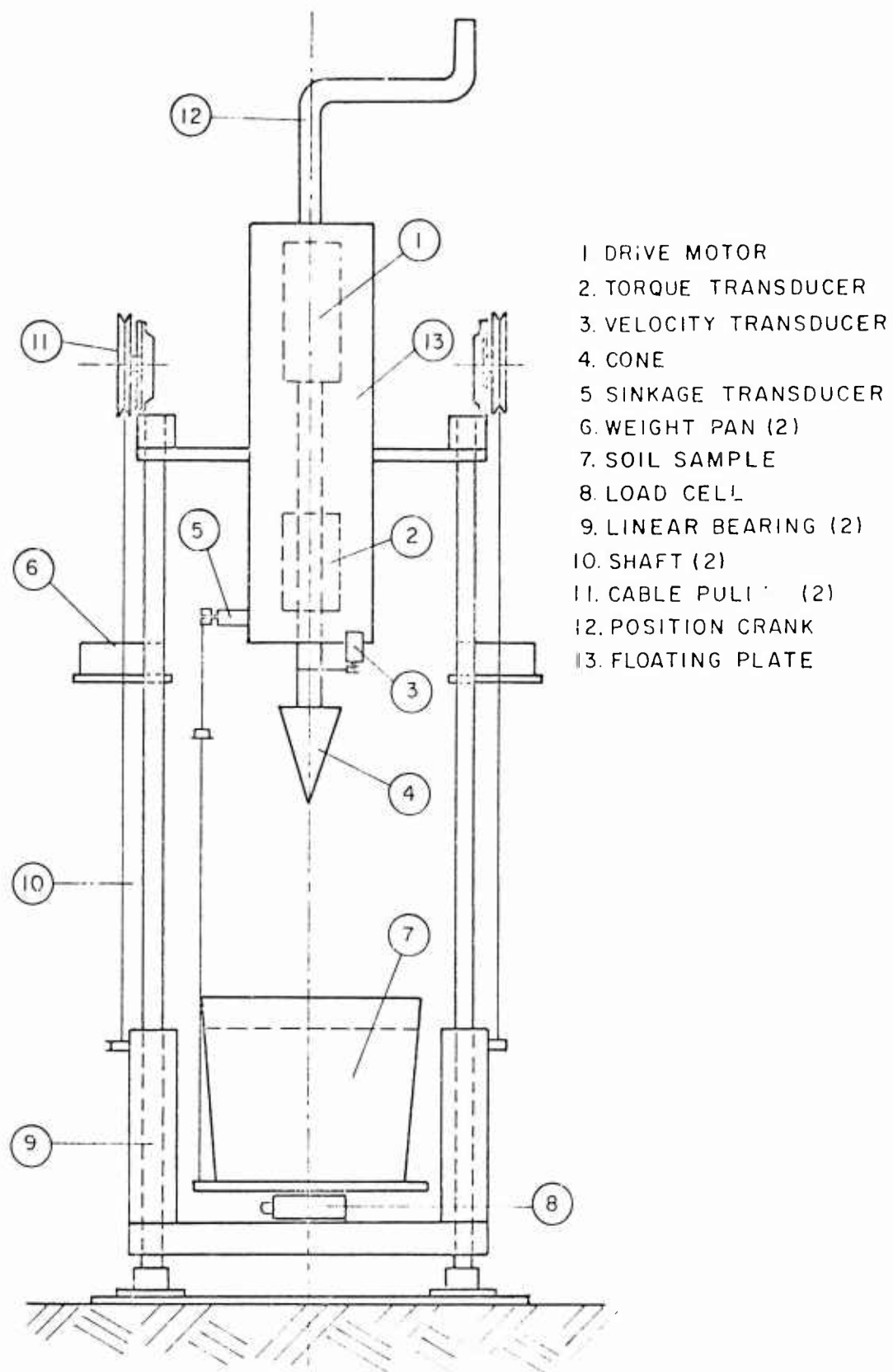


FIG. 1. SCHEMATIC DRAWING OF CORE TESTER

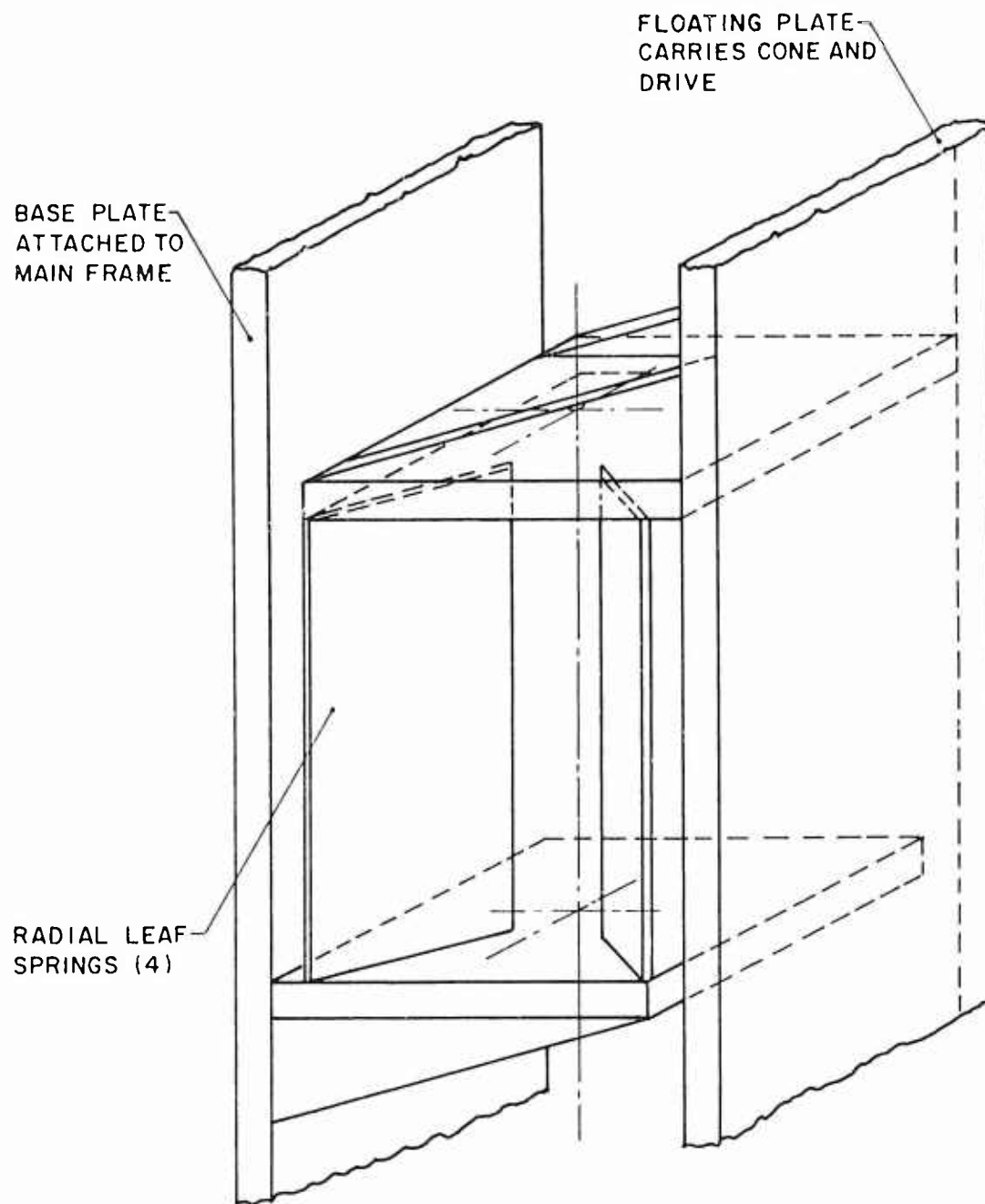
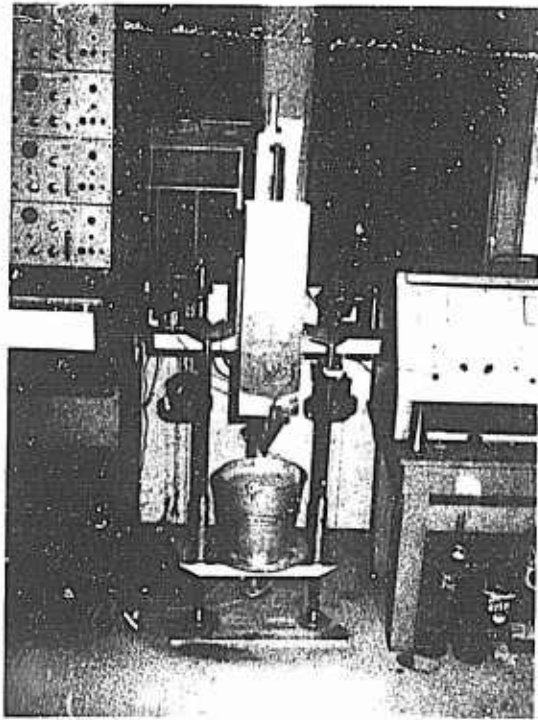
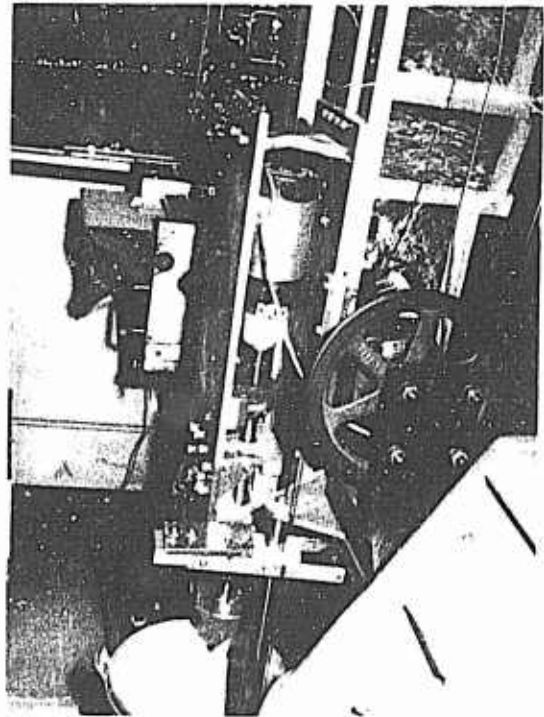


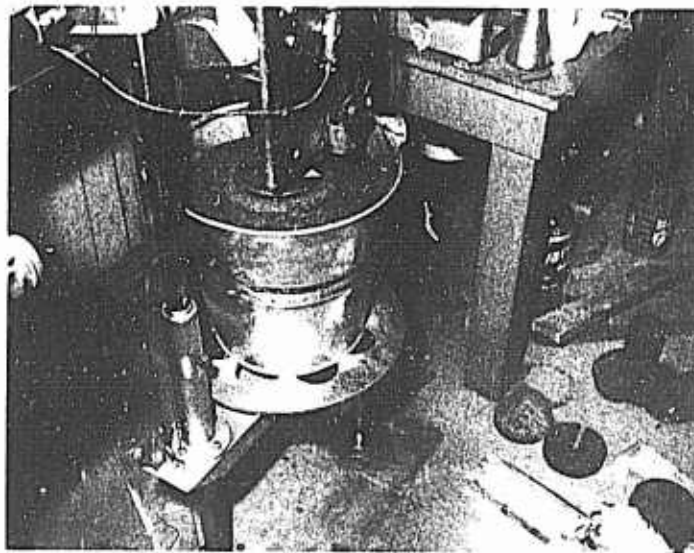
FIG. 2. DETAIL OF TORQUE BALANCE



a



b



c

FIGURE 3. THREE VIEWS OF THE ROTATING CONE SOIL TESTER

The following quantities were measured during a test:

1. the penetration force on a cone
2. the torque needed to rotate the cone
3. the rotational velocity
4. the sinkage of the cone

Preliminary calculations indicated the following ranges:

1. torque values up to 6 lb-in
2. weight (penetration force) up to 15 lb
3. rotational velocity up to 2500 rpm
4. sinkage up to 4 in

The equipment consisted of the following items:

1. cone drive and test stand
2. control system for cone drive
3. data recording system

Sinkage is measured by means of a 10-turn potentiometer through a special non-slip wire running between a reference point on the base plate of the cone drive to the sample platform. It is zeroed for every test by using the position crank. Zero sinkage was taken when the cone point touched the soil surface. The velocity was measured by a tach-generator attached to the base plate.

All measurements were recorded on a Sanborn 150 strip chart recorder. The drive system consists of an EC MOTOMATIC DC servo motor generator with a control panel. The capacity of the motor is 80 oz in. In the beginning, it was felt that torque could be measured through the control system of the motor, but this was abandoned. Also the original framework

allowed too many vibrations and inaccuracies in measurement of the sinkage  $H$  which is extremely critical, since  $H$  appears in the third and second power in the calculations of the shear stress  $\tau$  and the normal stress  $\sigma$  (see Reference 1 and Equations (1), page ).

#### SOIL SAMPLES

The soil was initially tested in round containers which measured  $6'' \times 6\frac{1}{2}''$  (large size coffee cans). The sand was processed after each penetration-rotation test by thoroughly mixing and then shaking it a certain number of times. The grain size distribution is given in Figure 4.

For the wet samples, the sand was mixed and shaken and then allowed to reach uniform conditions by aging between 16 to 20 hours. Samples were taken before and after every test and moisture content determined by weighing the sample before and after oven drying.

The shaking equipment consisted of an 1800 rpm electric motor mounted on a wooden plate. The motor shaft had a small eccentric weight attached to it. The vibration thus generated did an excellent job of compacting the sample. By timing the duration of the vibration, different densities could be obtained which were very consistent.

#### RESULTS AND DISCUSSION OF PRELIMINARY TESTS

Two series of preliminary tests were run during which several improvements were made to method and equipment.

Various moisture contents and densities were tested.

All tests were performed at the basic standard velocity  $V_0 = 20$  rpm.

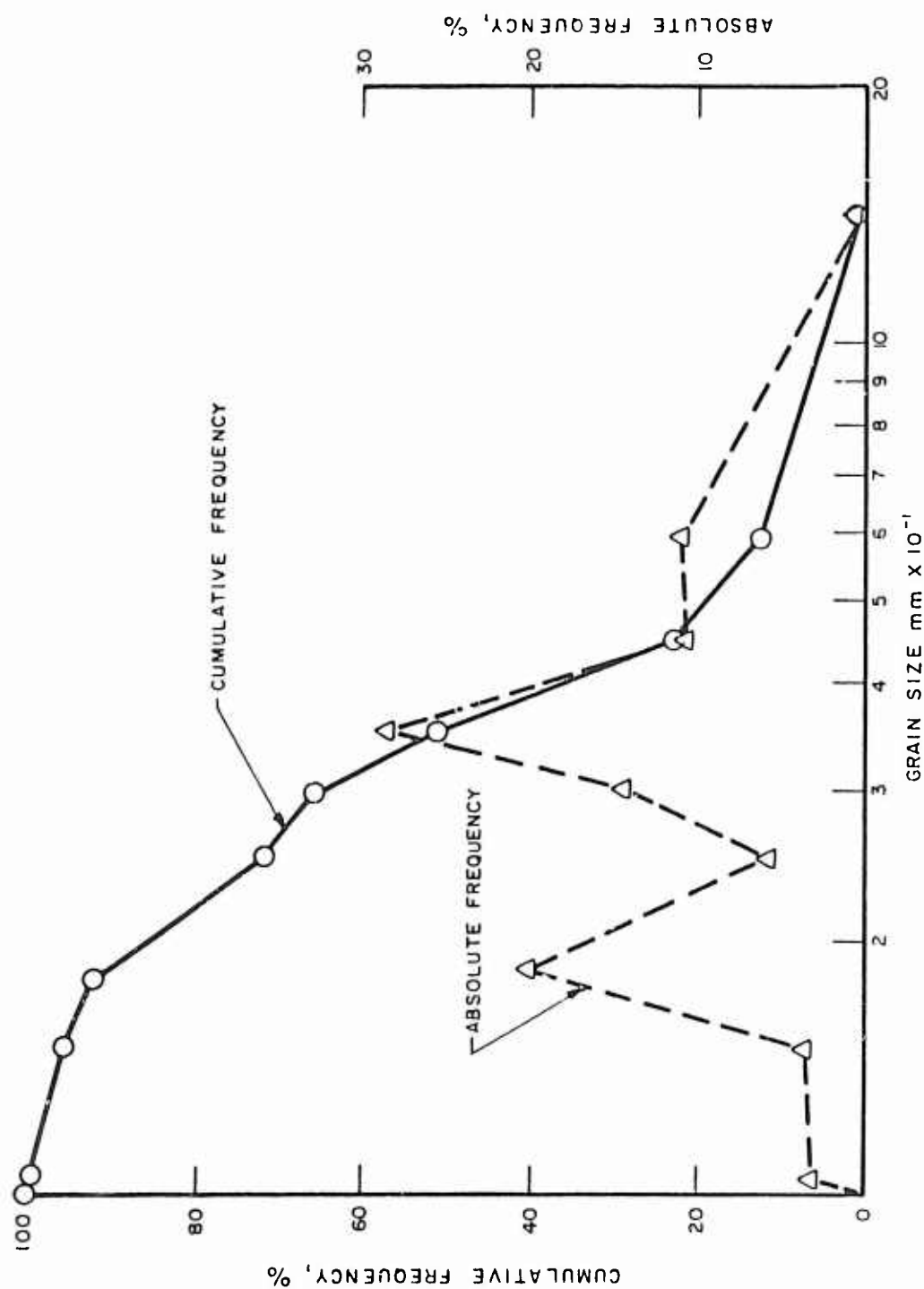


FIGURE 4. PARTICLE SIZE DISTRIBUTION

The resulting data showed a large amount of scatter. It was concluded that the scatter in the data was mainly caused by the interference between the cones and the sides and bottom of the container.

Subsequent tests were therefore carried out in buckets measuring 10" by 10" which were filled with 9" of sand. The data thus obtained showed considerably less scatter for both cones.

DETERMINATION OF STANDARD  $\alpha_0$  AND  $\mu_0$ 

The standard values of  $\alpha_0$  and  $\mu_0$  were determined at a basic standard velocity of rotation,  $V_0$ . This velocity was selected on the basis of the lowest practical and stable velocity the test set-up could maintain. It was found to be 20 rpm.

Plots of the  $\tau$  versus  $\sigma$  obtained from the experiments are presented in Figures 5 and 6.

Here

$$\begin{aligned}\tau &= C_1 \frac{T}{H^3} \\ \sigma &= C_2 \frac{W}{H^2}\end{aligned}\tag{1}$$

where  $T$  = the measured torque applied to the cone

$W$  = the measured vertical load on the cone

$H$  = the measured sinkage of the cone tip below the surface

$C_1, C_2$  = constants dependent upon the apex angle of the cone<sup>(1)</sup>

In order to understand the causes of the data scatter exhibited in Figures 5 and 6 analysis was made using a stepwise multivariate regression technique employing moving averages to fit a curve to the experimental values. To do this, averages of experimental values of  $T$  and  $H$  were plotted against average values of  $W$ . Smooth curves drawn through these data were then used to obtain one value of  $T$  (called the curve value,  $T_c$ ) and one value of  $H$  ( $H_c$ ) for each value of  $W$ . The ratios

$$R_T = \frac{T}{T_c} \text{ and } R_H = \frac{H}{H_c}$$

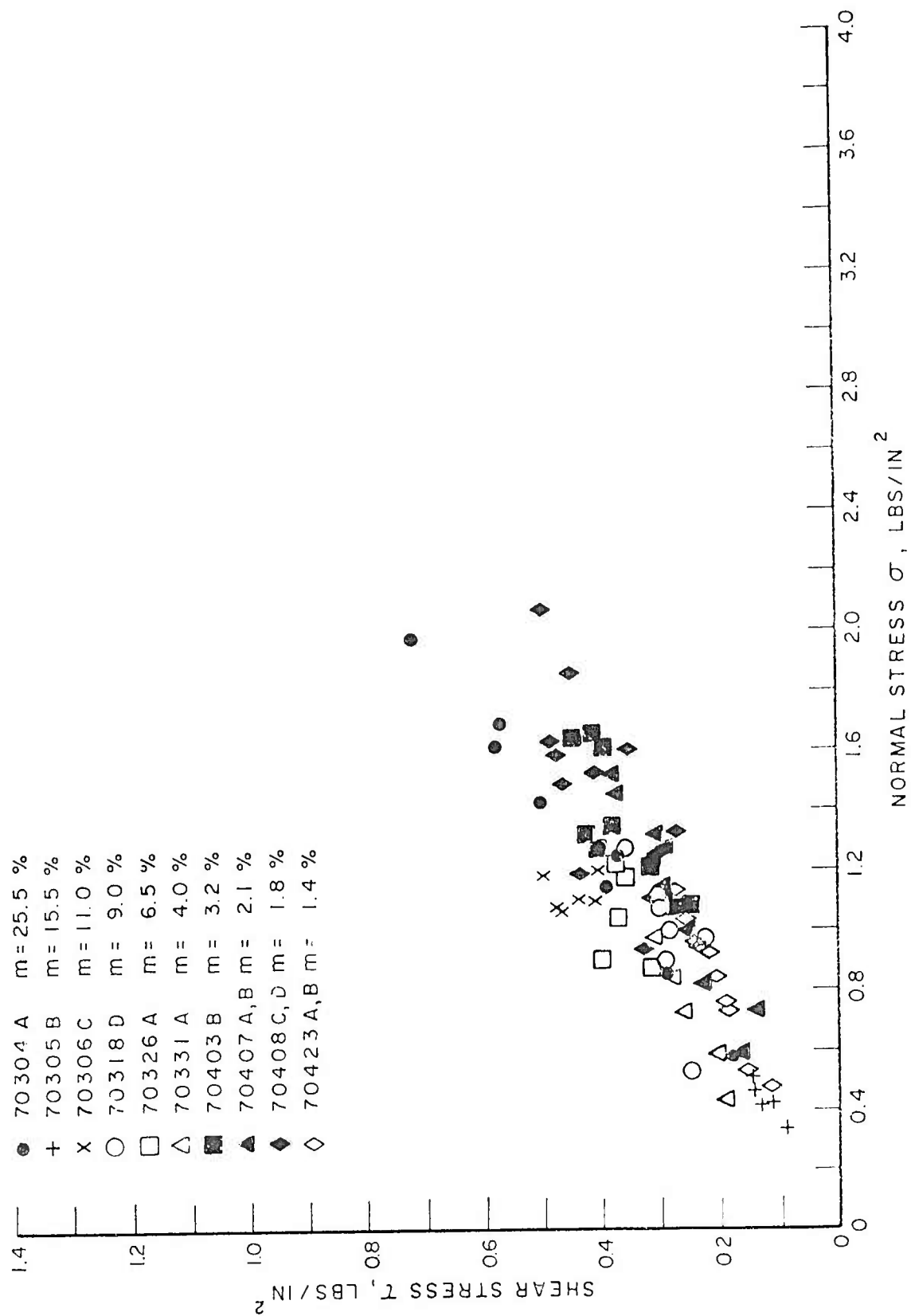
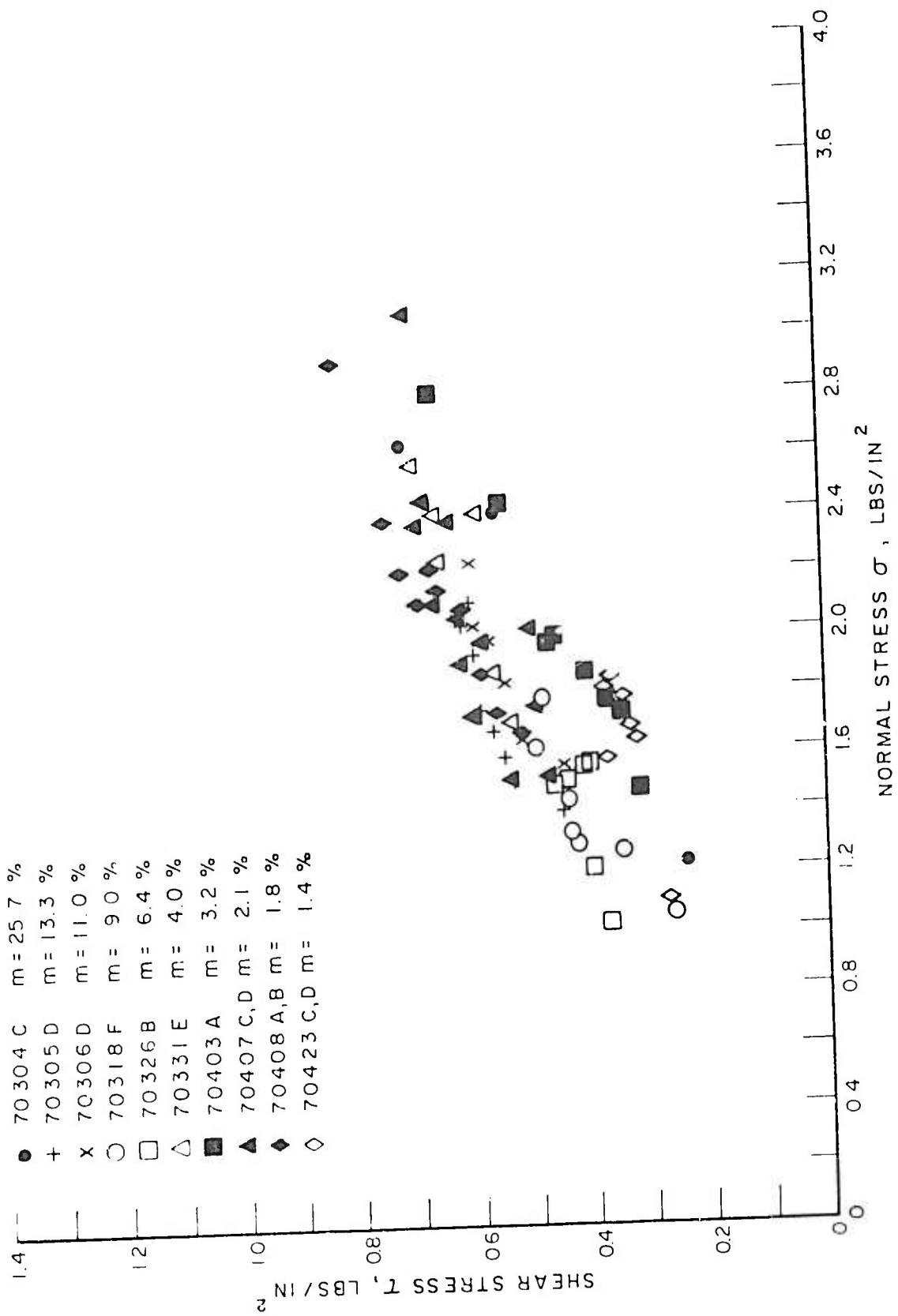


FIG. 5.  $\tau$  VERSUS  $\sigma$ , RELATIONS FOR A 60° CONE

FIG. 6.  $\tau$  VERSUS  $\sigma$ , RELATIONS FOR A 30° CONE

were then computed and plotted against each other.

Figure 7 shows three possible results of such an analysis. In Figure 7a the conclusion would be that  $R_T$  is independent of  $R_H$  i.e., the experimental values of  $T$  scatter about their expected values independent of the scatter of  $H$  about  $H_C$ . If the data group as shown in Figure 7b, it would indicate that, at values of  $H$  below the expected value  $H_C$ , the  $T$  values are higher than expected, thus indicating an inverse relationship. The relationship depicted in Figure 7c shows the inverse of that shown in Figure 7b. The scatter along the band, in the direction of the arrows, indicates that some other parameter influences the phenomenon. In most cases this would be some uncontrolled or badly controlled test condition.

Since in our case the variables which are included in the analysis are  $W$ ,  $\gamma$  and  $m$ , it is to be expected that the data would group themselves in moisture-density related clusters on the  $R_T$  and  $R_H$  plots. Similarly, two different cone shapes should show the angle effect if it exists. In Figures 8 and 9 two test series were carried out for each cone. The loose soil was prepared by stirring and loosening air dry sand in the large sample can. The dense sample was obtained by using the vibrator for 25 seconds on the same air dry sand.

The density in each case as measured by a cone penetrometer over a 3" depth was:

Loose:  $G = 4 \text{ psi/in}$

Dense:  $G = 15 \text{ psi/in}$

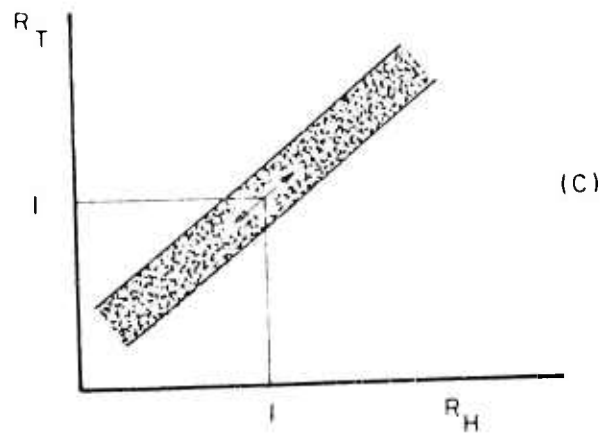
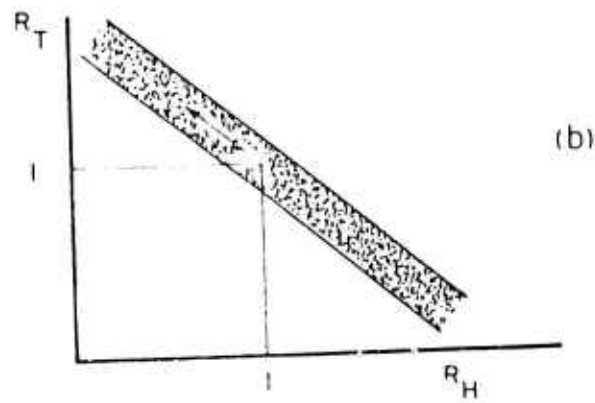
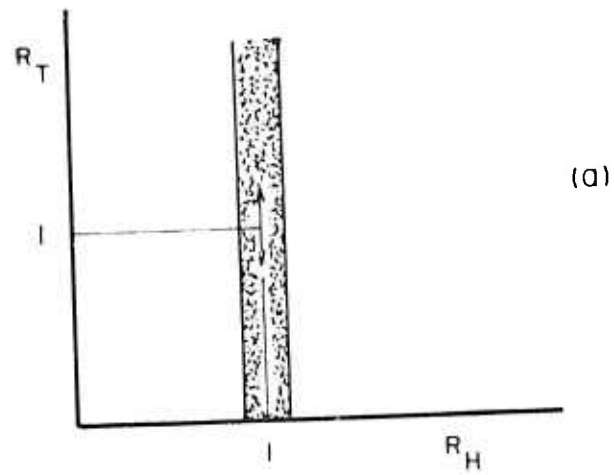


FIG. 7. EXAMPLES OF RELATIONSHIPS BETWEEN  $R_T$  AND  $R_H$

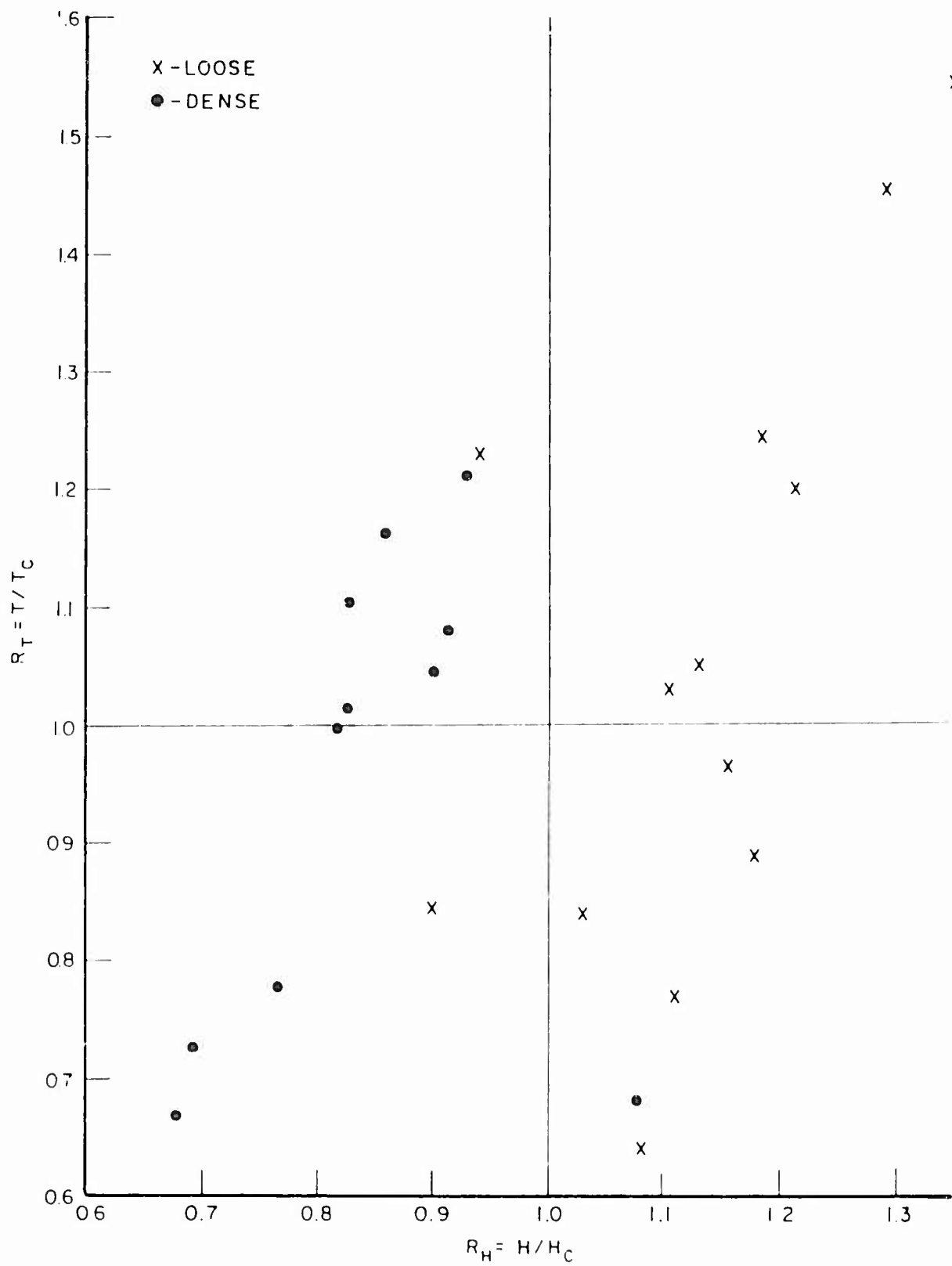


FIG. 8. RELATIONSHIP FOR A 30° CONE IN DRY SAND

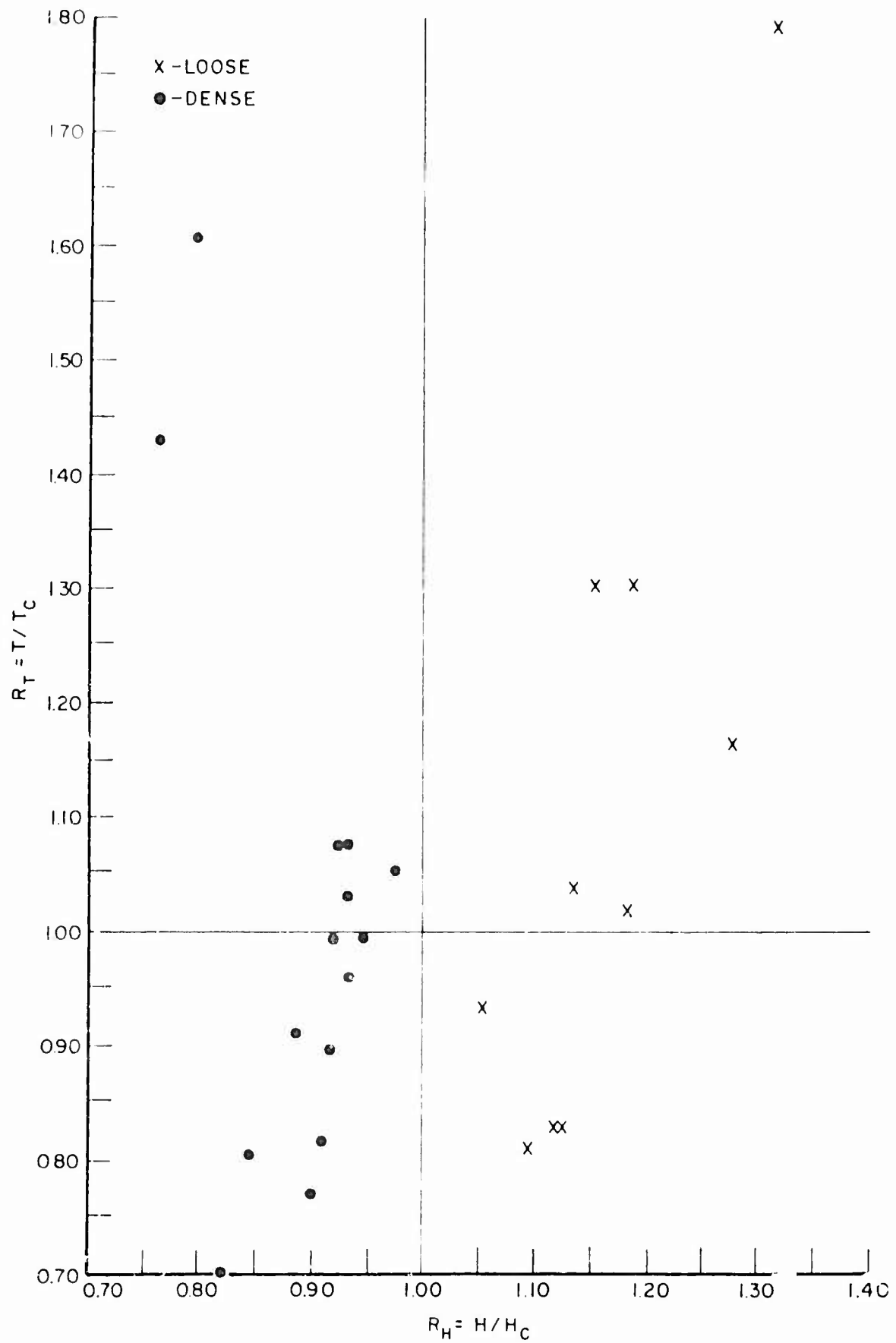


FIG. 9. RELATIONSHIP FOR A 60° CONE IN DRY SAND

From the figures, it is clear that scatter in the  $R_H$  direction is due to density. For both cones there is a distinct polarization. It was to be expected that the experimental sinkage value would be smaller than the overall expected sinkage value for the denser material, since the overall value includes both sets of data.

The scatter in the  $R_T$  direction is thus a result of other influences on the T-H relation, since moisture is a constant for both the loose and dense conditions. It can be seen that within each density, the torque  $T$  tends to increase with respect to the expected torque value,  $T_c$ , when the sinkage  $H$  increased with respect to the expected sinkage value,  $H_c$ , which is logical. The word "expected" should be interpreted here in the following manner. Since the values of  $T_c$  and  $H_c$  were calculated for the same load  $W$  it is to be expected that the actual data points will spread themselves with some amount of scatter about this point. Since this point is not really an average in the usual sense, it was felt appropriate to call this central value the expected value.

In Figures 10 and 11 the  $R_T$  versus  $R_H$  plots for a series of tests at low but varying moisture content are given. In these tests attempts were made to keep the density constant, but it can be seen, especially in the  $60^\circ$  cone test, that in some of the tests, notably 704080, the density control was poor, thus causing a more pronounced scatter in the  $R_H$  direction. The  $30^\circ$  cone data (Figure 9) show that the scatter about the expected value of  $T(R_T = 1.0)$  was independent of the scatter about the expected value of  $H(R_H = 1.0)$ . The graph also shows that for the depicted moisture range no conclusions can be drawn as to the effect of moisture. This is no doubt partly due to the interaction of moisture and density.

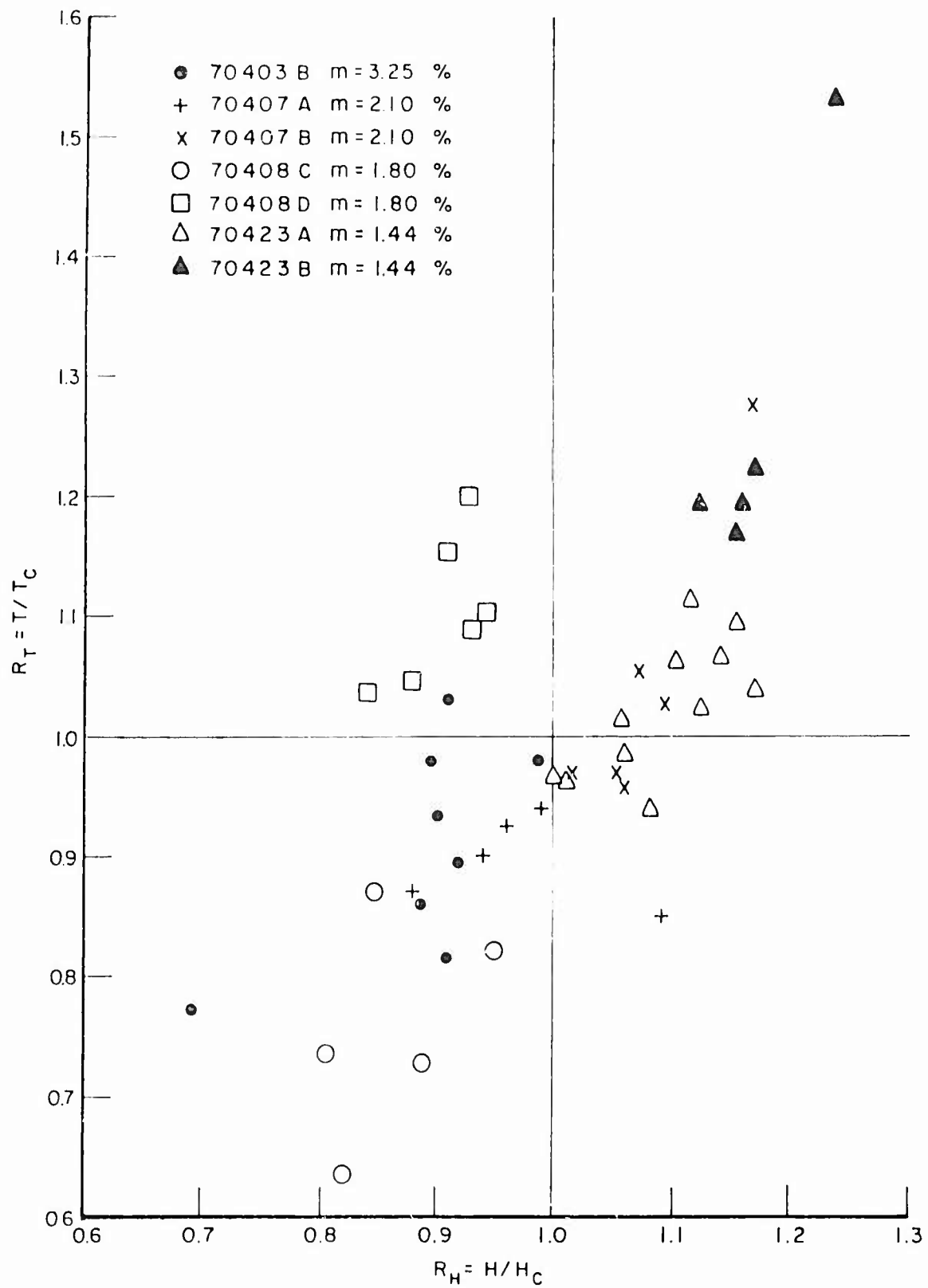


FIG. 10. RELATIONSHIP FOR A 60° CON<sup>-</sup> AS A FUNCTION OF MOISTURE CONTENT

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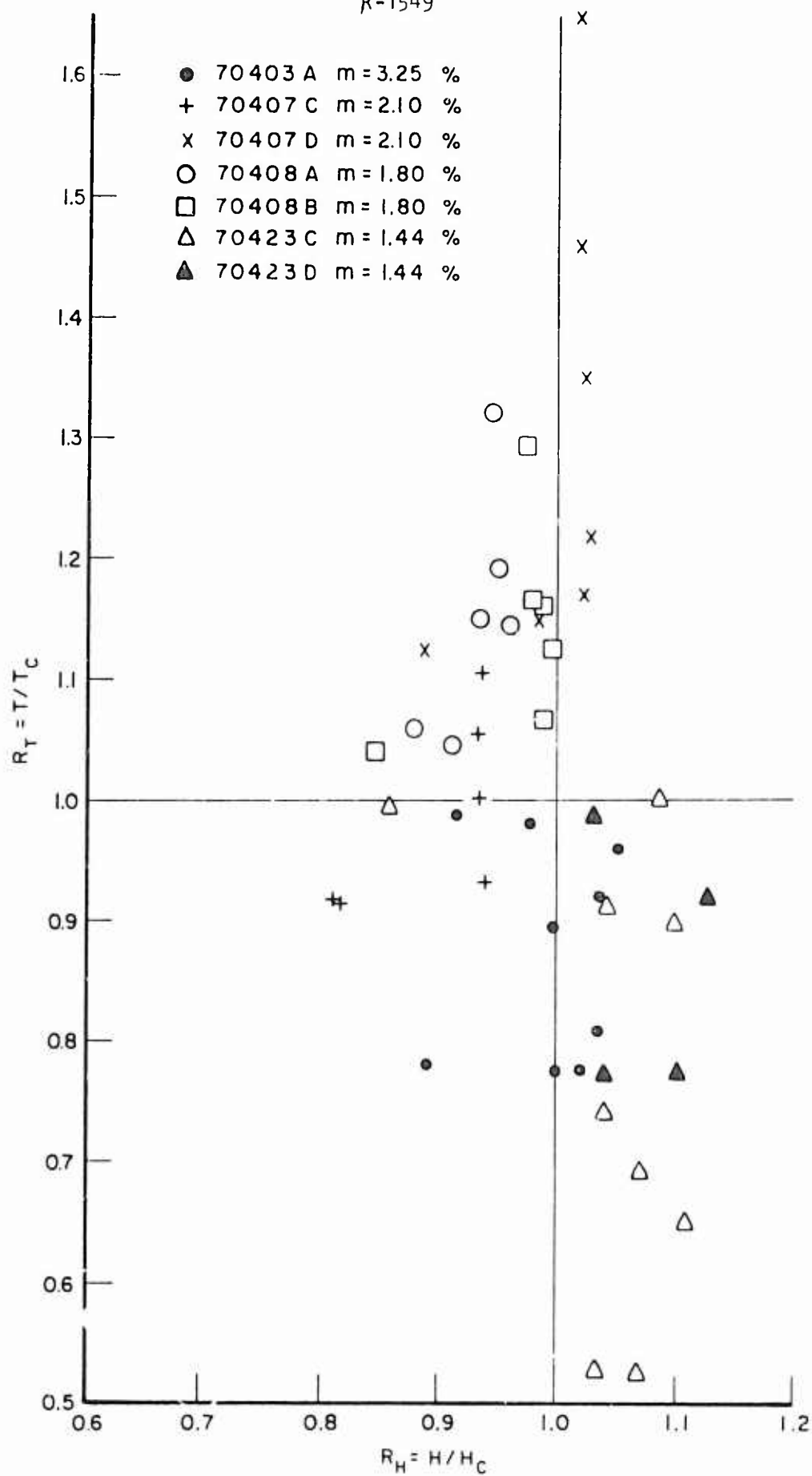


FIG. II. RELATIONSHIP FOR A 30° CONE AS A FUNCTION OF MOISTURE CONTENT

It was however felt that the other reason for this scatter was the interference between the container and the cone. This interference would also show up differently for the  $30^\circ$  and  $60^\circ$  cones.

All subsequent tests, embodying the main part of the investigation and described in the next chapter, were performed in enlarged containers. The resulting analysis of the data showed a sharp reduction in the scatter.

From Figures 5 and 6, the conclusion can be drawn that for most of the range of values, the relationship between  $\tau$  and  $\sigma$  is linear.

A regression analysis of the data which was run on the computer gave the following results:

1.  $60^\circ$  Cone

$$\text{Equation } \tau = .001 + .297 \sigma$$

$$\text{F-Value} = 270$$

$$\text{Degrees of Freedom} = 86, 1$$

$$\text{Standard Error of Estimate} = .07$$

$$\text{Correlation Coefficient} = .87$$

2.  $30^\circ$  Cone

$$\text{Equation } \tau = -.008 + .277 \sigma$$

$$\text{F-Value} = 100$$

$$\text{Degrees of Freedom} = 78, 1$$

$$\text{Standard Error of Estimate} = .100$$

$$\text{Correlation Coefficient} = .75$$

The above data show that:

- a) The  $30^\circ$  Cone had more scatter than the  $60^\circ$  Cone.

- b) The  $\tau$ -axis intercept appeared to be very small. The standard error of the estimate is large in both cases compared to the intercept value. Thus, for the test conditions as described, the value of  $C_1$  may be taken as zero.

## EFFECTS OF VELOCITY

Soil Conditions

The sand was kept at two moisture contents: air dry and saturated (27% by weight). The density of the air dry sand was varied with the vibrator described in Section 3. The density levels were defined as Loose, Medium and Dense, which conformed to volume weight,  $\gamma$ , of 92, 100 and 109 lb/ft<sup>3</sup>, respectively.

The wet sand had a constant density which was determined by the saturation moisture content. To attain greater uniformity, these samples were also vibrated.

Velocity Conditions

The velocities at which the tests were run ranged from about 20 rpm to 2000 rpm. The velocity was set on the DC control panel and was measured continuously by means of a tachometer-generator. Thus variations of the velocity could be observed during the test.

## TEST METHOD - VELOCITY EFFECTS

Two methods of testing were used and the results were analyzed with the aim of determining whether different results were obtained.

Method 1: The soil was processed to the desired density and was reprocessed for each new velocity.

Method 2: The soil was not reprocessed for each velocity. From the viewpoint of ease of testing, the second method is preferable since the sample is not taken out of the tester and the cone stays in place over the whole range of velocities. On the other hand, there is no knowledge about any change of density during testing and because of the test itself. Only the initial density is known.

The first method requires more time since, for each test, the sample has to be reprocessed or a new sample has to be inserted. Some amount of scatter will be introduced due to the variation in density between the samples for each test, as was brought out also in preceding sections.

## RESULTS AND DISCUSSION OF VELOCITY TESTS

### Dry Sand

Results for the tests are shown in Figures 12 through 17. They include data obtained by both test methods described in the preceding section. This inclusion was judged justified after analysis did not show significant difference. Further proof was found after the data were plotted, since the total scatter appears to be very limited in magnitude.

The first conclusion from the results is that for a steel cone-sand system, the relationship between  $\tau$  and  $\sigma$  is independent of the velocity, since all points fall along the same curve and no grouping along the curve is evident. For the dry soils at all three densities, and for both cones, the relationship can be expressed as

$$\tau = C_1 + C_2 \sigma$$

with  $C_1$ , as expected, having a very low value. The values of the constants for the dry soil, are given in table 1.

From Table 1, the following can be concluded:

- a. The value of  $C_1$  for the  $30^\circ$  cone is very small. The standard error of the estimate is large compared to  $C_1$  and includes the zero.

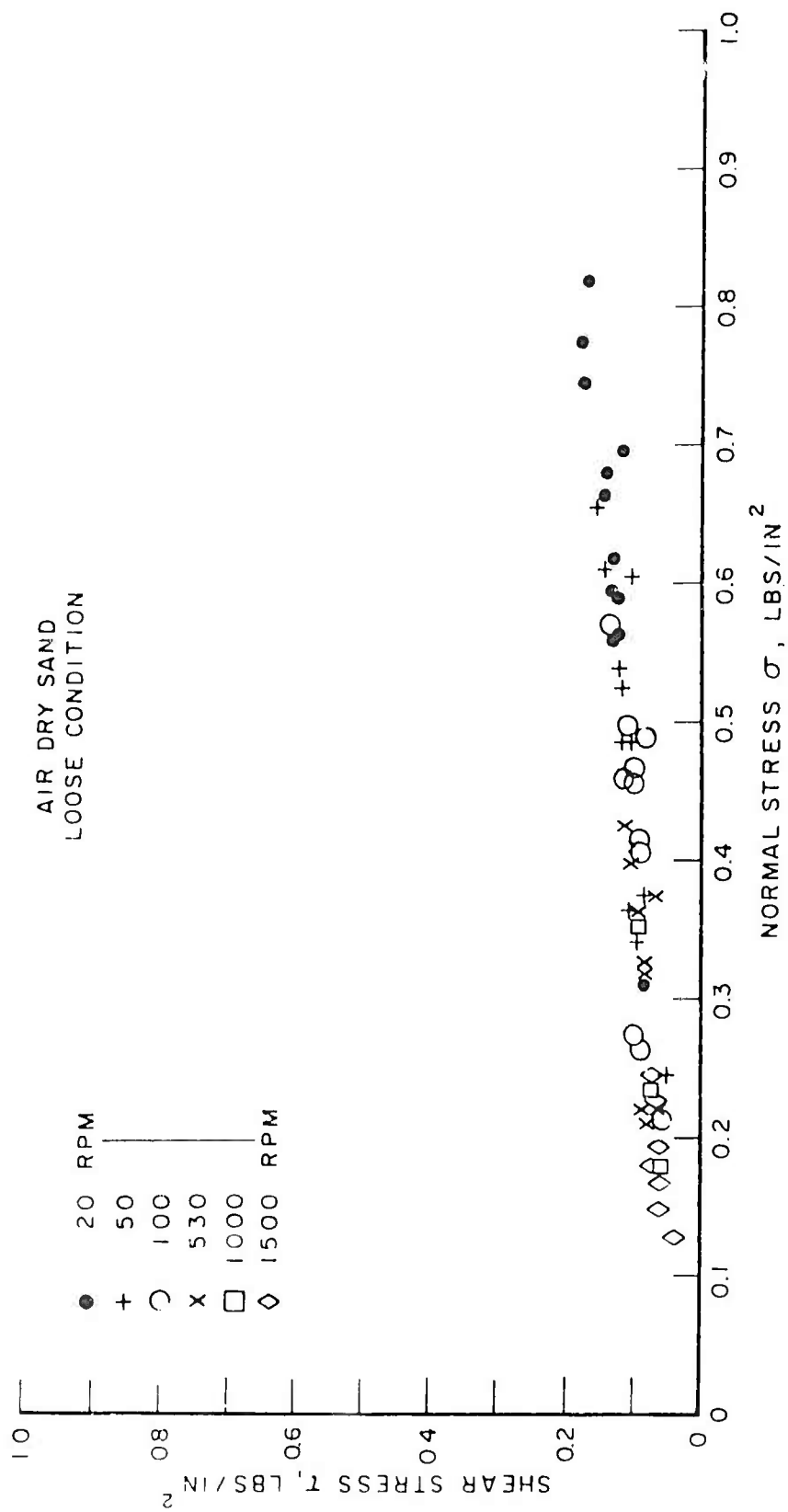


FIG. 12. SHEAR STRESS VS NORMAL STRESS RELATIONSHIP AT VARYING VELOCITIES-60° CONE

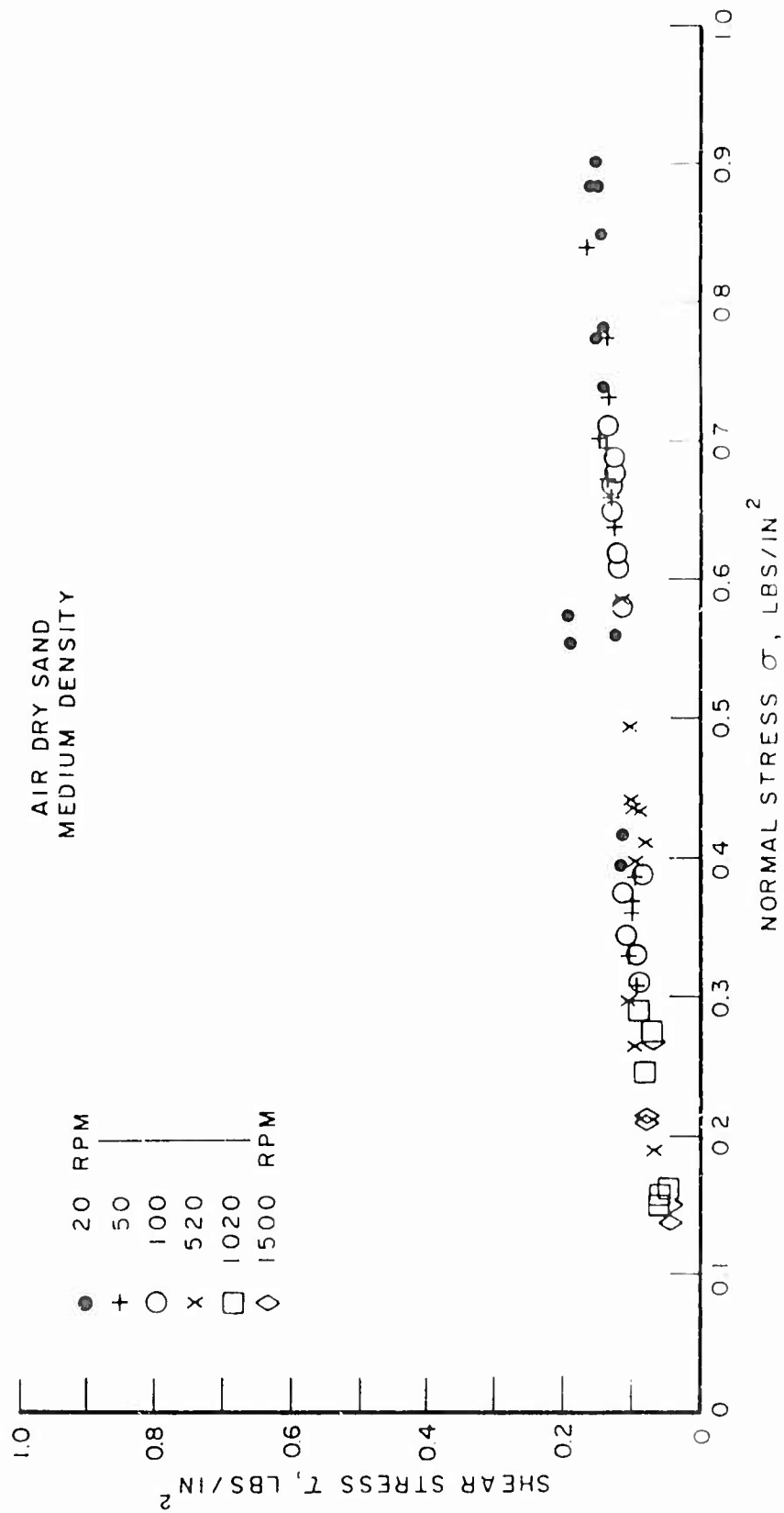


FIG. 13 SHEAR STRESS VS NORMAL STRESS RELATIONSHIP AT VARYING VELOCITIES - 60° CONE

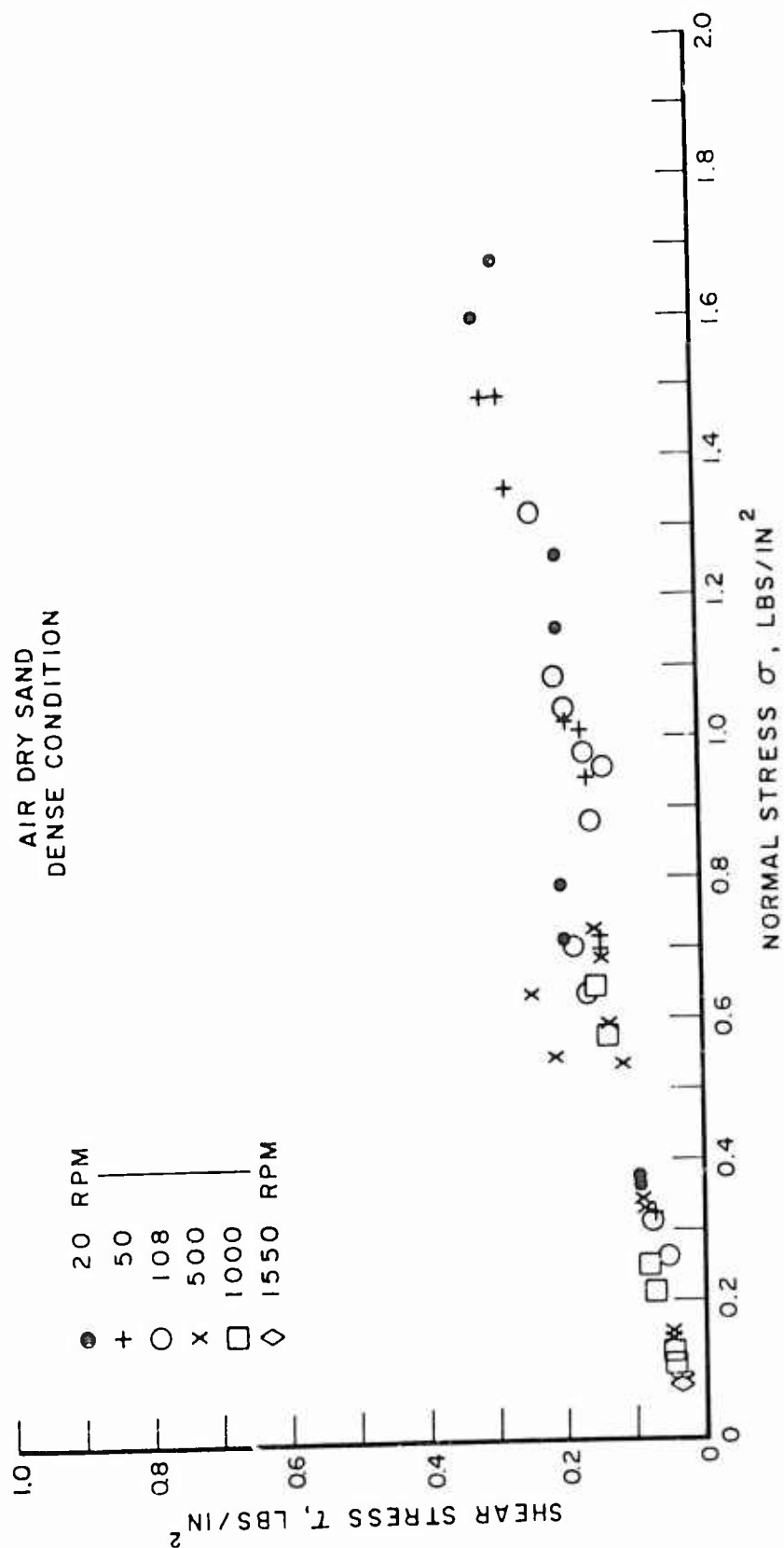


FIG. 14. SHEAR STRESS VS NORMAL STRESS RELATIONSHIP AT VARYING VELOCITIES -60° CONE

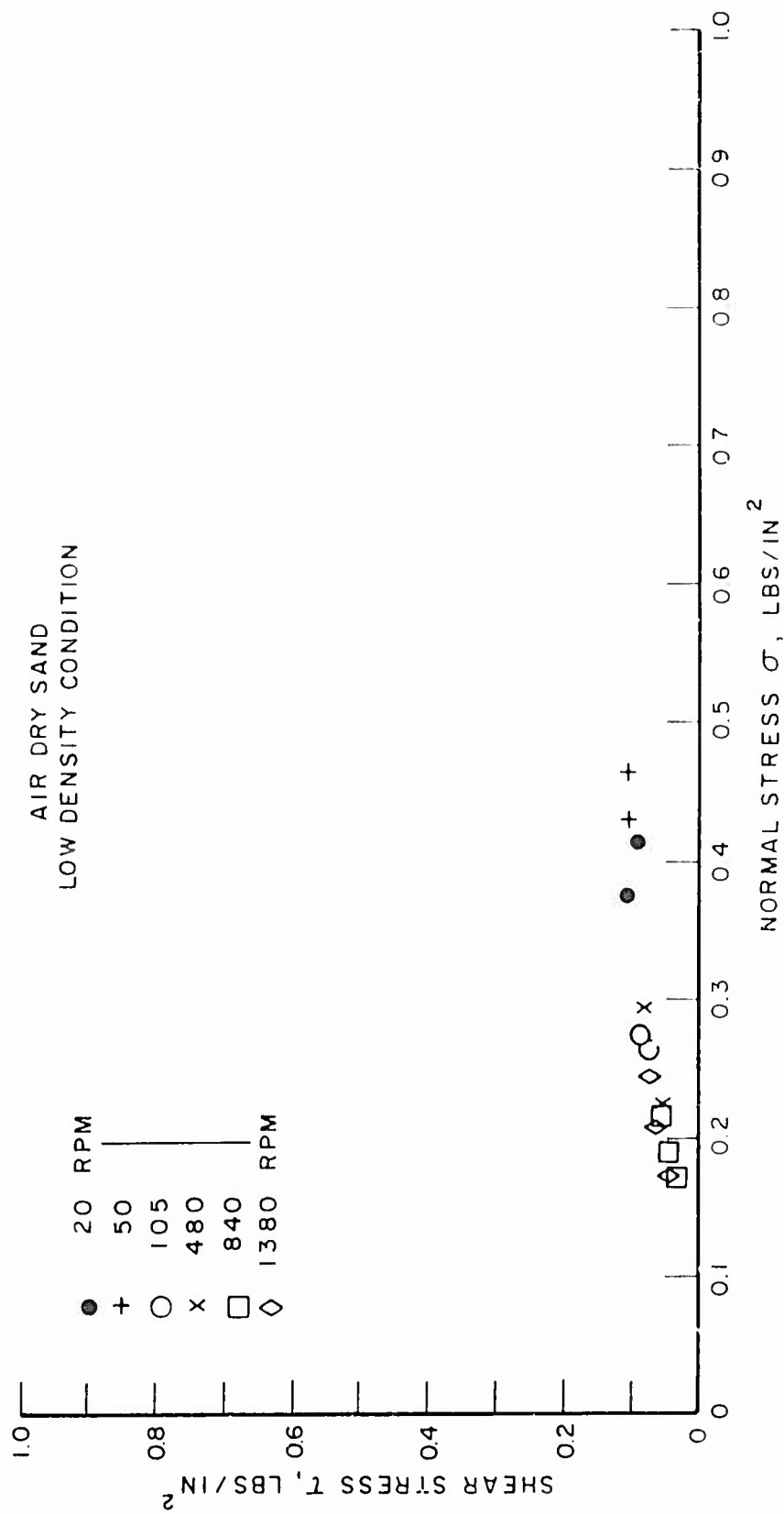


FIG. 15. SHEAR STRESS VS NORMAL STRESS RELATIONSHIP AT VARYING VELOCITIES - 30° CONE

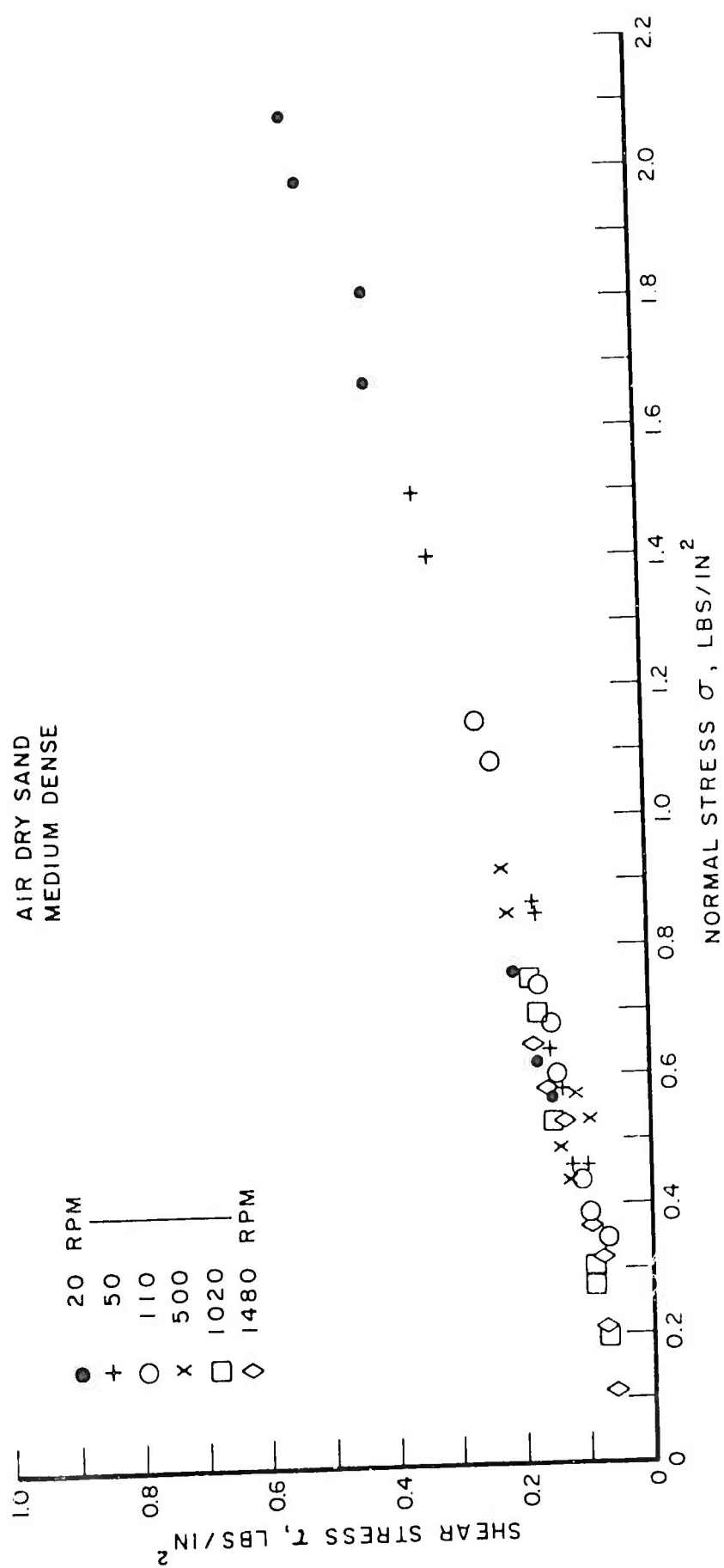


FIG. 16. SHEAR STRESS VS NORMAL STRESS RELATIONSHIP AT VARYING VELOCITIES - 30° CONE

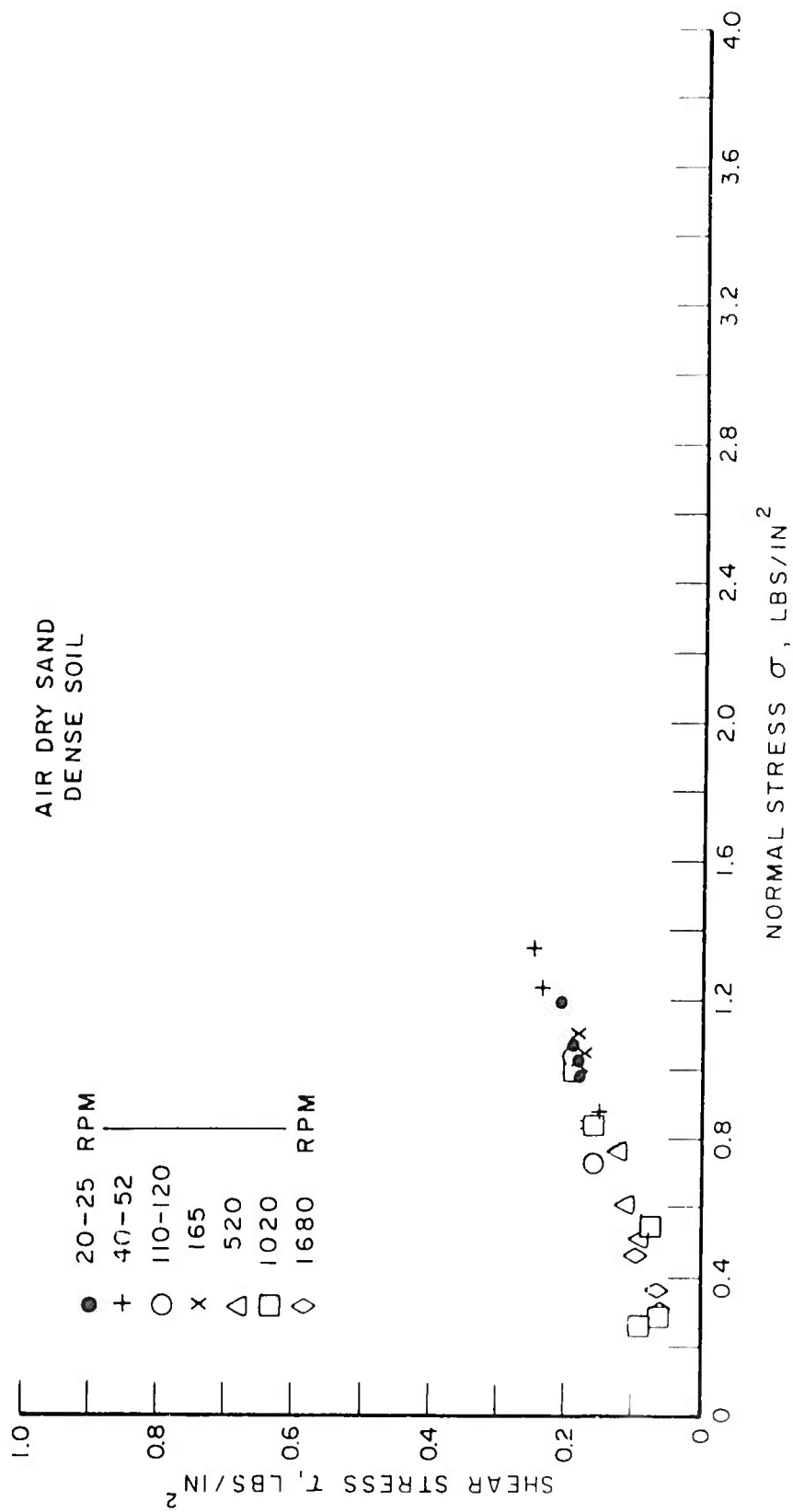


FIG. 17. SHEAR STRESS VS NORMAL STRESS RELATIONSHIP AT VARYING VELOCITIES-30° CONE

Table 1  
VALUES FROM LINEAR REGRESSION ANALYSIS FOR VELOCITY TESTS - DRY SAND

Test Condition Angle	Density	Intercept $C_1$	Slope $C_2$	Correlation Coefficient $r$	Standard Error of Estimate $\bar{S}$	F-Value $F$	Degrees of Freedom $df$
30°	Loose	.011	.220	.91	.012	56.5	12, 1
	Medium	.005	.24	.98	.020	1416	44, 1
	High	.007	.174	.98	.013	463	22, 1
	Avg	.007	.217	---	---	---	---
60°	Loose	.021	.170	.91	.013	300	61, 1
	Medium	.045	.132	.95	.010	531	58, 1
	High	.036	.150	.97	.020	650	44, 1
	Avg	.037	.150	---	---	---	---

b. The value of  $C_1$  for the  $60^\circ$  cone is small but appears to be significantly different from zero.

c. The differences between the  $C_2$  values from within each cone do not give a clue with respect to their trend. No conclusion can be made regarding the variation of  $C_2$  with density.

d. The difference between the  $C_2$  values for each cone cannot be determined although the average value for the  $60^\circ$  cone appears to be lower than the average value for the  $30^\circ$  cone.

Both figures and table show that the scatter for these series was much less than for the preliminary tests. This is undoubtedly due to the experience gained in controlling test conditions.

For a dry, sandy soil no cohesive or adhesive properties, as defined in the usual sense, would be expected to exist. Thus the values of  $C_1$  for the  $30^\circ$  cone would be in accord with this surmise. It does appear, however, that due to the particular test conditions, some pseudo-cohesive effect exists in the case of the  $60^\circ$  cone, since the values of  $C_1$  here appear to be different from zero. This does not necessarily mean that for a larger apex angle, the  $C_1$  value would increase. It is conceivable that a maximum exists somewhere between the  $30^\circ$  cone and a flat plate (a cone apex angle of  $180^\circ$ ).

The value of  $C_2$  is dependent by definition on the material properties of the interface and thus it would be expected that they would be identical for both cones. However, since no particular care was taken in the polishing of the cones, some differences in  $C_2$  values may be due to surface roughness variations.

### Calculation of $\alpha$ and $\mu$ -Values and Their Velocity Dependence

The values of  $\alpha$  and  $\mu$  were defined in a preceding paper<sup>1</sup> as:

$$\alpha = \frac{C_1}{2/3 - \cot g (\theta/2)} \quad (2)$$

$$\mu = \frac{C_2}{\frac{n+2}{n+3} - C_2 \cot g (\theta/2)} \quad (3)$$

In Table II, the values at  $\alpha$  and  $\mu$  are calculated from the  $C_1$  and  $C_2$  values of Table I. It is evident that the assumptions made in developing Equations 2 and 3 are not borne out by the test results. There is no rational explanation for negative values for either  $\mu$  or  $\alpha$  as obtained for the  $30^\circ$  cone. The principal reason for this appears to be the sensitivity of the denominator of both equations to the magnitude of  $C_2$ .

#### Saturated Sand

The data for the tests with saturated sand are shown in Figures 18 and 19. It is evident that a linear relation with a positive intercept does not exist.

A Regression Analysis to fit a quadratic to the data gave the following results:

1.  $30^\circ$  Cone

$$\tau = - .033 + .218\sigma + .003\sigma^2$$

Correlation Coefficient = .98

Standard error of estimate = .055

F-value = 328

Degrees of Freedom = 26,2

Table 11  
CALCULATED  $\alpha$ - AND  $\mu$ -VALUES ( $n=1$ )

<u>Test Conditions</u>		$C_1$	$C_2$	$\alpha$	$\mu$
Angle	Density	lb/in <sup>2</sup>		lb/in <sup>2</sup>	
30°	Loose	.011	.22	negative	negative
	Medium	.005	.24	"	"
	Dense	.007	.174	"	1.74
60°	Loose	.031	.170	.083	.373
	Medium	.045	.132	.102	.253
	Dense	.036	.150	.088	.305

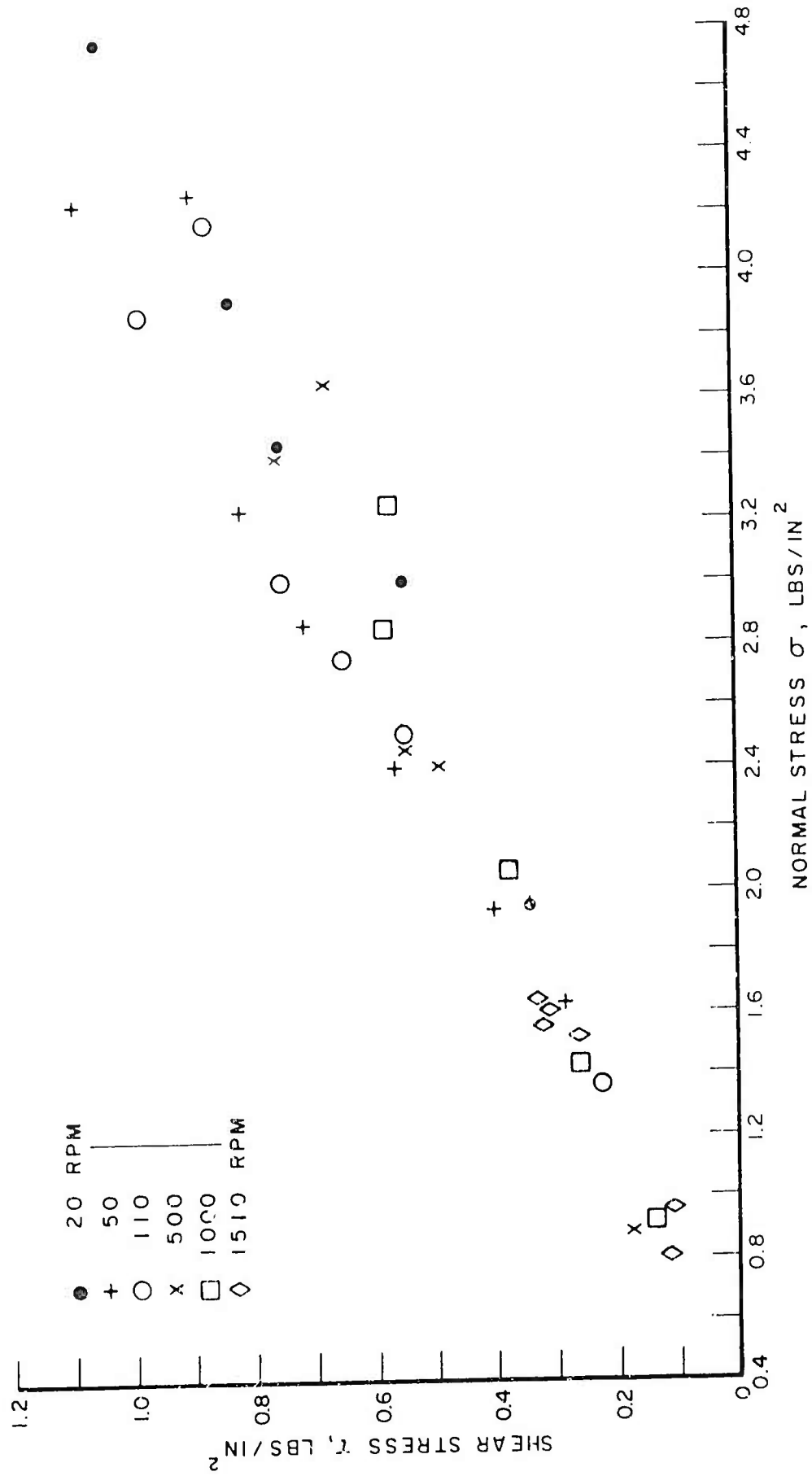


FIG. 18. SHEAR STRESS VS NORMAL STRESS RELATIONSHIP AT VARYING VELOCITIES-30° CONE

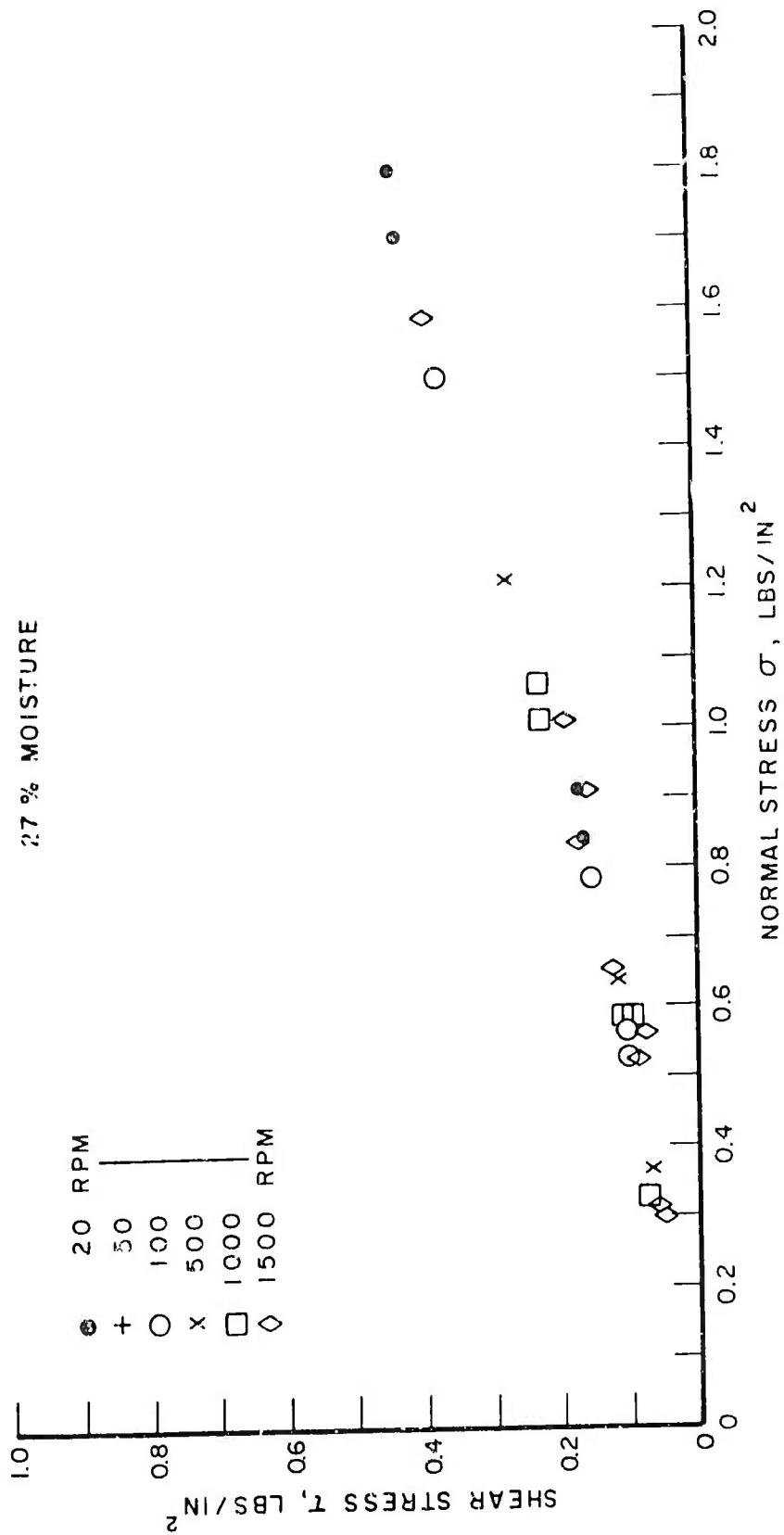


FIG. 19. SHEAR STRESS VS NORMAL STRESS RELATIONSHIP AT VARYING VELOCITIES-60° CONE

## 2. 60° cone

$$\tau = .021 + .091\sigma + .09\sigma^2$$

Standard error of estimate = .011

Correlation coefficient = .99

F-value = 1017

Degrees of freedom = 21,2

the intercepts again are small and the standard error of the estimate is rather large by comparison although not as pronounced for the 60° cone.

In general, the data from the 60° cone tended to show less scatter. During the tests, it was observed that the 60° cone tests were easier to carry out because of smaller penetration. From these tests no definite conclusions can be made regarding the character and interpretation of the three constants. More data over a wider range of moisture contents are required.

## CONCLUSIONS

From the tests with wet and dry sand the following conclusions can be formulated:

- 1) There appears to be a linear relationship between the shear stress on a normal stress for the cone in sand.
- 2) The assumptions made for the development of equations 2 and 3 are not borne out by the test results; this is partly due to the sensitivity of those equations to the slope factor  $C_2$  of the test data.
- 3) The relationship between  $\tau$  and  $\sigma$  does not appear to be influenced by velocity for a sand in the dry or saturated condition.

## RECOMMENDATIONS

It is recommended that funds be made available to carry out further investigations of the following points:

1. A wider range of moisture content for a sand in order to define more clearly the parameters obtained.
2. Interface parameters and their velocity dependence for cohesive and mixed soils at various moisture contents.
3. Interface parameters and their velocity dependence for coated cones in various soils at various moisture contents.
4. Performance of tests with wheels and reduction of data using dimensional analysis methods in order to incorporate the interface parameters into a prediction equations system.

## REFERENCES

1. Leviticus, L. I. and Ehrlich, I. R., "The Rotating Cone Soil Test: A proposed Method to Determine Velocity Dependent Properties of the Soil Wheel Interface," Davidson Laboratory Report SIT-DL-71-1511 and ASAE Paper 70-660.
2. Crenshaw, B.M. "Soil/Wheel Interaction at High Speed, ISTVS-SAE Paper 710181-1971.
3. Turnage, G. W. and D. R. Freitag, "Effects of Cone Velocity and Size on Soil Penetration Resistance," ASAE paper No. 69-670.

## Appendix

## 1. SORTING PROGRAM (Only for Themis)

```

    DIMENSION N(50), IVS(2000), VEL(2000),
2  TAU(2000), SIGMA(2000)
    INTEGER TESTNO
    CALL IFILE(20, 'CONEV')
    CALL OFILE(21, 'COUT')
    I=0
    II=1
    READ(20,24) KA,KD,KM,KV
24  FORMAT(4I)
32  READ (20,20) TESTNO,DIG,ID,SOIL,THETA,DENS,WATER
    IF (EQFC(20)) GO TO 30
20  FORMAT(I5,A1,I1,A4,F3,0,A3,F)
    IF (TESTNO.EQ.0,0) GO TO 30
    IF (THETA.EQ.30,0) K=KA
    IF (THETA.EQ.60,0) K=2*KA
    IF (DENS.EQ.'DNS') K=K+KD
    IF (DENS.EQ.'MED') K=K+2*KD
    IF (DENS.EQ.'LSE') K=K+3*KD
    IF (WATER.EQ.0,0) K=K+KM
    IF (WATER.GT.0,0.AND,WATER.LE,5,0) K=K+2*KM
    IF (WATER.GT.5,0.AND,WATER.LE,10,0) K=K+3*KM
    IF (WATER.GT.10,0.AND,WATER.LE,15,0) K=K+4*KM
    IF (WATER.GT.15,0.AND,WATER.LE,20,0) K=K+5*KM
    IF (WATER.GT.20,0.AND,WATER.LE,25,0) K=K+6*KM
    IF (WATER.GT.25,0.AND,WATER.LE,30,0) K=K+7*KM
    IF (WATER.GT.30,0.AND,WATER.LE,35,0) K=K+8*KM
    IF (WATER.GT.35,0.AND,WATER.LE,40,0) K=K+9*KM
    TANG=SIND(THETA/2,)/COSD(THETA/2,0)
    SECA=1./COSD(THETA/2,0)
31  READ(20,21) T,W,V,H
21  FORMAT(4F)
    IF (T.EQ.0,0) GO TO 33
    I=I+1
    TAU(I)=T/(3.142*(TANG**2)*SECA*(H**3))
    SIGMA(I)=W/(3.142*TANG**2)*(1./(H**2))
    IVS(I)=INT(V)*KV+K+I
    VEL(I)=V
    GO TO 31
33  N(II)=I
    II=II+1
    GO TO 32

```

```

30 NDAT=I
   DO 41 I=1,NDAT-1
   DO 41 J=1,NDAT
   IF (IVS(I).GT,IVS(J)) GO TO 41
   IT1=IVS(I)
   T2=TAU(I)
   T3=SIGMA(I)
   T4=VEL(I)
   IVS(I)=IVS(J)
   TAU(I)=TAU(J)
   SIGMA(I)=SIGMA(J)
   VEL(I)=VEL(J)
   IVS(J)=IT1
   TAU(J)=T2
   SIGMA(J)=T3
   VEL(J)=T4
41 CONTINUE
   WRITE (21,22)
   EMU1=TAU(1)/SIGMA(1)
   DO 42 I=1,NDAT

      EMU=TAU(I)/SIGMA(I)
      RMU=EMU/EMU1
      RVEL=VEL(I)/VEL(1)
42 WRITE(21;23) IVS(I),TAU(I),SIGMA(I),EMU,RMU,RVEL
23 FORMAT(3X,I12,5F9.4)
22 FORMAT(1H1,'HEADING COMES HERE',5(/))
   CALL EXIT
   END

```

The program will sort according to the moisture content, density, cone angle, and velocity. The sorting is done according to a code, defined by the input constants KA, KD, KM and KV. The magnitude of these constants determines the magnitude and location of the variable.

For instance:

The number 1011012018 is obtained by setting

KA =	1,000,000,000
KD =	1,000,100
KM =	10,000,000
KV =	100

and signifies that this test is for a  $30^\circ$  cone, 0.01 moisture, dense sand, velocity of 120 rpm and belongs to test set number 18.

## 2. REGRESSION PROGRAM

```

      DIMENSION X(400),TAU(100),SIG(100),STD(5),XBAR(5),D(10)
      +          ,ISAVE(5),RX(16),RY(4),LV(4),MV(4),B(4),SB(4),T(4)
      +          ,ANS(10),R(10)
10  I=1
      TYPE 3
      3 FORMAT(' ENTER INPUT BLOCK'/)
20  ACCEPT 1,TAU(I),SIG(I)
      IF(TAU(I).EQ.99)GO TO 21
      I=I+1
      GO TO 20
21  N=I-1
      DO 23 I=1,N
          X(I)=SIG(I)
          X(I+N)=SIG(I)**2
          X(I+2*N)=SIG(I)**3
23  X(I+3*N)=TAU(I)
      M=4
      IO=1
      CALL CORRE(N,M,IO,X,XBAR,STD,RX,R,D,B,T)
      TYPE 2,(X(I),X(I+N),X(I+2*N),X(I+3*N),I=1,N)
      DO 30 K=1,3
      DO 25 J=1,K
25  ISAVE(J)=J
      KP1=K+1
      CALL ORDER(KP1,R,4,K,ISAVE,RX,RY)
      CALL MINV(RX,K,DET,LV,MV)
      CALL MULTR(N,K,XBAR,STD,D,RX,RY,ISAVE,B,SB,T,ANS)
      TYPE 4,(ANS(I),I=1,10),(B(I),SB(I),T(I),I=1,K)
30  CONTINUE
      GO TO 10
      1 FORMAT(2F)
      2 FORMAT(34(4F/))
      4 FORMAT(4F/4F/2F/3(3F/))
      END
      SUBROUTINE DATA
      RETURN
      END

```

This program is set up to be used on the teletype with a PDP-10 computer. Data are entered in pairs of  $\tau, \sigma$  on the teletype.

The subroutines Corre, Order, Minv and Mult, are standard SSP subroutines - see IBM application Program H20-0205-3.

The output of this program is as follows:

1. Input data are repeated and  $\sigma^2$  and  $\sigma^3$  values are printed out.

2. ANS(I) I = 1, 10

ANS 1 = Intercept

2 = Multiple Correlation Coefficient

3 = Standard Error of Estimate

4 = SSAR (Regression)

5 = DF Associated with SSAR

6 = Mean Square of SSAR

7 = SSRD (Deviations from regression)

8 = DF Associated with SSRD

9 = Mean Square of SSRD

10 = F-Value

3. B(I), SB(I), T(I) I = 1, K

B(I) = first column at the regression constants

SB(I) = second column - the standard duration associated with B(I)

T(I) = third column - the t-value associated with B(I)